

Power Efficiency and Delay Tradeoff of 10GBase-T Energy Efficient Ethernet Protocol

Xiaodan Pan, Tong Ye, *Member, IEEE*, Tony T. Lee, *Fellow, IEEE*, and Weisheng Hu, *Member, IEEE*

Abstract—In this paper, we study the power efficiency and delay performance of the IEEE 802.3az Energy Efficient Ethernet (EEE) protocol. A new approach is proposed to analyze the M/G/1 queue with the vacation time that is governed by the arrival process and the parameter τ and N of the BTR strategy. Our key idea is to establish the connection between the vacation time and the arrival process to account for their dependency. We first derive the distribution of the number of arrivals during a vacation time based on an event tree of the BTR strategy, from which we obtain the mean vacation time and the power efficiency. Next, from the condition on the number of arrivals at the end of a vacation period, we derive a generalized P-K formula of the mean delay for EEE systems, and prove that the classical P-K formula of the vacation model is only a special case when the vacation time is independent of the arrival process. Our analysis demonstrates that the τ policy and N policy of the BTR strategy are compensating each other. The τ policy ensures the frame delay is bounded when the traffic load is light, while the N policy ensures the queue length at the end of vacation is bounded when the traffic load is heavy. These results, in turn, provide the rules to select appropriate τ and N . Our analytical results are confirmed by simulations.

Index Terms—Ethernet, IEEE802.3az, EEE protocol, M/G/1 queue with vacation, P-K formula.

I. INTRODUCTION

AS a fundamental and pervasive network component, Ethernet has been widely applied to various kinds of networks, such as data center networks, local area networks (LANs), metropolitan area networks (MANs) and wide area networks (WANs). The number of Ethernet devices is huge [1], and growing with the evolution of network technologies [2]. Meanwhile, it is estimated that the data rate of Ethernet increases at the pace of one order of magnitude every 10 years [3], which significantly increases the power consumption of each Ethernet device. For example, the power consumption of a 1000Base-T Ethernet interface is only 0.5W [4], while that of a 10GBase-T interface is 5W [5]. Therefore, with the increase of the data rate, the huge number of Ethernet devices have imposed a heavy burden on the power consumption of communication networks.

On the other hand, Ethernet interfaces are idle most of the time. The link utilization of an Ethernet interface is only about 5%-30%, as described in [6], [7]. The design of the IEEE 802.3az standard [8], also called the Energy Efficient Ethernet (EEE) protocol, aims to relieve the power

consumption of Ethernet devices. The key idea of the EEE protocol is to shut down some components of the Ethernet interface during idle periods to reduce power consumption. In other words, the interface will switch off some components, such as transceivers, and enter a so-called low power idle (LPI) mode through a Sleep operation once the transmission buffer is empty. It will wake up its components through a Wakeup operation when it accumulates enough frames in the buffer. The interface requires high power to implement the Sleep and Wakeup operations, but does not have any contributions to frame transmissions. Moreover, the durations of the Sleep and Wakeup periods are comparable to the transmission time of a frame. Thus, to maximize the power efficiency of the EEE protocol, as Fig. 1 illustrates, the frequency of the Sleeps and the Wakeups should be limited.

Recently, a wakeup strategy called burst transmission (BTR) [9], [10] has attracted a lot of interest. The BTR strategy does not trigger the Wakeup at once when the first frame arrives after the beginning of the Sleep. Instead, the BTR strategy initializes a timer and a counter upon the first arrival and triggers the Wakeup when the timer or the counter reaches a predetermined threshold. The BTR strategy ensures that the duration of the LPI mode is sufficiently long, and the number of frames that can be transmitted after each Wakeup is sufficiently large, such that the power efficiency can be higher. However, when these thresholds become too large, the BTR strategy may worsen the delay performance, since the interface is not allowed to transmit the frames that arrive during idle periods. This implies that there is a tradeoff between the power efficiency and the queueing delay. The purpose of this paper is to study the influence of the two important BTR parameters, the timer threshold τ and the counter threshold N , on the system performance.

A. Previous work

Several analytical models have been developed to study the EEE protocol in recent years. The simplest case is considered in [11]–[13], in which $\tau = 0$ and $N = 1$, that is, the Wakeup is triggered by the first arrival frame. This kind of BTR strategy is also called frame transmission (FTR) scheme [10]. The time is slotted according to the frame transmission time and a discrete-time Markov chain is developed in Ref. [11], but it is very difficult to solve for a closed-form solution. Thus, this paper only obtains the power efficiency and does not derive the mean delay. Ref. [12] derives the power efficiency through a simple model, which cannot be extended to study the mean delay of a frame. To obtain both the power consumption and

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The authors are with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China. (email: {pxd0506, yetong, ttlee, wshu}@sjtu.edu.cn).

mean delay, a thorough analytical framework for the EEE systems with the link rate ranging from 100Mb/s to 10Gb/s is proposed in Ref. [13]. However, previous results reported in [9], [14] show that the FTR strategy does not work well and $\sim 86\%$ power is consumed by the Sleep and the Wakeup operations in the worst case.

Thus, Ref. [15] uses a deterministic model to estimate the performance of the BTR strategy with $\tau \rightarrow 0$ and $N > 1$, that is, only the counter is used. Despite this model obtaining both the power efficiency and the mean waiting time, it is less accurate when N is small. On the other hand, Ref. [16] considers the BTR strategy where only the timer is used. The waiting-time distribution and the power efficiency are derived in Ref. [16] based on a recursive relation between the waiting times of two consecutive frames.

The general case that includes both the timer and the counter was investigated in [10], [17]–[20]. To simplify the analysis, Ref. [17]–[20] consider two extreme regimes, low-load scenario and high-load scenario, based on the observation that the timer expires before the counter reaches threshold N if the traffic load is sufficiently low; otherwise, the counter triggers the Wakeup if the traffic load is high enough. The main drawback of these efforts is that they cannot obtain a unified expression of the power consumption and the mean delay over the whole traffic load regime. To fix this problem, Ref. [10] develops a model based on the renewal theory. In this paper, a sleep period followed by a busy period is considered as a renewal cycle. Though this paper assumes that frames will not arrive during the Sleep period, the derivation is still very complicated such that the results cannot provide a clear physical insight of EEE systems.

B. Our Approach and Contributions

In this paper, we analyze the BTR strategy of 10Gbase-T Ethernet, in which the two transmission directions are independent of each other. Our goal is to develop a unified model to predict the performance of the EEE protocol such that we can provide rules to select the proper values of parameter τ and N .

The BTR strategy is modeled as an M/G/1 queue with vacation time, which is governed by the frame arrival process via the timer threshold τ and the counter threshold N . First, we show that the classical M/G/1 queue with vacation time [21] cannot be directly applied to delineate the EEE protocol. We then develop a new approach to analyze the performance of the EEE protocol. Our key idea is to establish the connection between the vacation time and the arrival process to account for their dependency. We first derive the distribution of the number of arrivals during a vacation time based on an event tree of the BTR strategy, from which we obtain the mean vacation time and the power efficiency. Next, based on the number of arrivals at the end of the vacation, we derive a generalized P-K formula of the mean delay for EEE systems.

For a fixed traffic load, we find that the power efficiency converges to a constant while the mean delay is unbounded when τ and N increase, which means that τ and N should not be too large in the practical application of BTR strategy. Our

results clearly show that the timer and the counter are compensating for each other and play different roles in different traffic rate regions. The timer τ bounds the delay incurred by the vacation when the traffic rate is smaller than $(N-1)/\tau$, while the counter N limits the queue length during the vacation time when the load is larger than $(N-1)/\tau$. Therefore, for a given arrival rate λ , a proper choice of the parameters τ and N should satisfy the condition $(N-1)/\tau = \lambda$. Our specific contributions are summarized as follows:

1. We develop a new approach to analyze the M/G/1 queue with the vacation time that is governed by the arrival process and the parameters τ and N of the BTR strategy.
2. We derive a generalized P-K formula of mean delay for the M/G/1 queue with the vacation time controlled by the arrival process. We show that the classical P-K formula of mean delay is only a special case when the vacation time is independent of the arrival process.
3. We show that the τ policy and N policy of the BTR strategy are compensating each other. Our analysis demonstrates the impacts of parameters τ and N on the power efficiency and mean delay. These results provide the rules to select the appropriate τ and N .

The rest of this paper is organized as follows. In section II, we propose the vacation model which establishes the connection between the vacation time and the arrival process and derives the power efficiency of BTR strategy. In section III, we derive a generalized P-K formula of the mean delay which reduces to the traditional P-K formula when the vacation time is independent of the arrival process. In section IV, our model is validated by simulations. Furthermore, based on our analysis, we summarize two rules to select appropriate values of parameters. Section V concludes this paper.

The notations used in this paper are defined as follows:

- Parameters of the EEE protocol
 - T_s Duration of the Sleep
 - T_w Duration of the Wakeup
 - N Counter threshold
 - τ Timer threshold
 - φ_0 Power consumption (W per unit time) in LPI state
 - φ_1 Power consumption (W per unit time) in the busy period, Sleep and Wakeup
 - η Power efficiency
- System parameters
 - λ Frame arrival rate
 - μ Frame service rate
 - D Mean delay of a frame
- Variables in vacation model
 - a_n Probability that there are n arrivals during the Sleep and LPI periods
 - b_n Probability that there are n arrivals during the Wakeup period
 - h_n Probability that there are n packets in the buffer at the end of vacation
 - V Duration of a vacation
 - C Duration of a cycle
 - R_i Residual time for completing a vacation or a service seen by an arrival

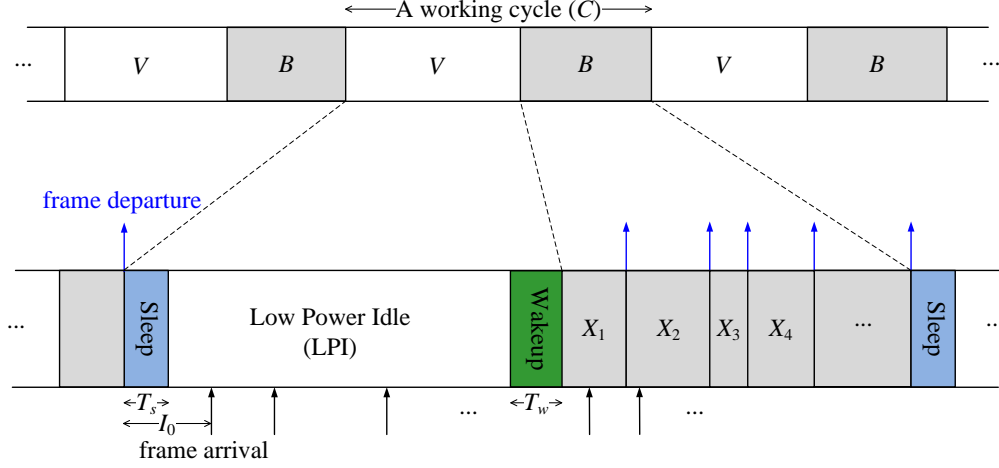


Fig. 1. The burst transmission (BTR) strategy of the 10GBase-T EEE protocol.

X_j Transmission (service) time of the j th frame

II. VACATION MODEL OF EEE PROTOCOL

The process of the BTR strategy implemented on a 10GBase-T EEE interface in one direction of a link is a sequence of cycles, as Fig. 1 shows, each of which consists of a vacation period followed by a busy period. The cycle, vacation period, and busy period are respectively denoted by C , V and B . Each cycle begins when the transmission buffer becomes empty and the interface enters a vacation period. First, the interface turns off its transmitter through a Sleep operation, during which the interface is still in the high power mode, and the power consumption is denoted as φ_h . The duration time of the Sleep operation is $2.88\mu s$, denoted as T_s . As specified in the 10GBase-T EEE protocol, the Sleep operation is uninterruptible. After the Sleep operation, the interface goes into an LPI (low power idle) mode, in which the power consumption is only $\varphi_l = 0.1\varphi_h$. During the vacation period, the system initializes a timer and a counter when the first frame arrives, and the counter increases by one for each new arrival. As soon as the timer reaches the threshold τ or if there are N frames waiting in the buffer, the vacation period terminates and the interface turns on its transmitter through a Wakeup operation. Similar to the Sleep operation, the Wakeup operation lasts a constant duration, $4.48\mu s$, denoted as T_w , with the same power consumption φ_h . After the Wakeup operation, the interface starts the busy period, during which the frames are transmitted until the buffer becomes empty.

Depending on the selections of parameters τ and N , the BTR strategy can be further divided into several policies. If $\tau \rightarrow \infty$, the BTR strategy is referred to as N policy [22], which wakes up the interface by the counter threshold N . Similarly, if $N \rightarrow \infty$, the BTR strategy is called τ policy [23], which wakes up the interface by the timer threshold τ . The BTR strategy is called $\tau\&N$ policy as both τ and N are finite. The basic idea of this policy is to guarantee that the delay and the backlogged queue length are both bounded.

It is clear that the interface is a queueing system with vacation time; the interface goes to sleep (or takes a vacation)

once the buffer becomes empty. However, unlike the classical queueing model with vacation time, where the vacation time and the arrival process are statistically independent, the vacation time of the Ethernet interface with the BTR strategy is completely governed by the frame arrival process through τ and N policies.

As the vacation time is determined by the number of arrivals during the vacation period, which is regulated by timer τ and counter N , our analysis of the BTR strategy starts with the derivation of the distribution of the number of arrivals during the vacation time, from which we derive the mean vacation time, the power efficiency, and the queuing delay. In modeling the BTR strategy, we adopt the following assumptions:

- The input traffic is a Poisson process with arrival rate λ ;
- The interface transmits the frames in a first in first out (FIFO) manner;
- The frame transmission times X_1, X_2, \dots are independent and identically distributed random variables with first and second moments \bar{X} and \bar{X}^2 , respectively;
- The threshold τ is larger than the duration of Sleep T_s , because T_s is very short and the timer $\tau \leq T_s$ is meaningless.

A. Vacation Model

As we mentioned above, the key to model the BTR strategy is the number of arrivals during vacation period V , whose distribution is defined as follows:

$$h_n = Pr\{n \text{ arrivals during a vacation period } V\}.$$

The vacation period is divided into two independent parts. The first part, denoted as V_{SL} , consists of the Sleep and the LPI periods, while the second part is the Wakeup T_w . Accordingly, the number of arrivals during vacation period V is the sum of the number of arrivals during V_{SL} and that during T_w .

The tree depicted in Fig. 2 describes the complete arrival events that occurred during V_{SL} . We show in the following lemma that the distribution of the number of arrivals during V_{SL} is determined by parameters τ , N , and arrival rate λ .

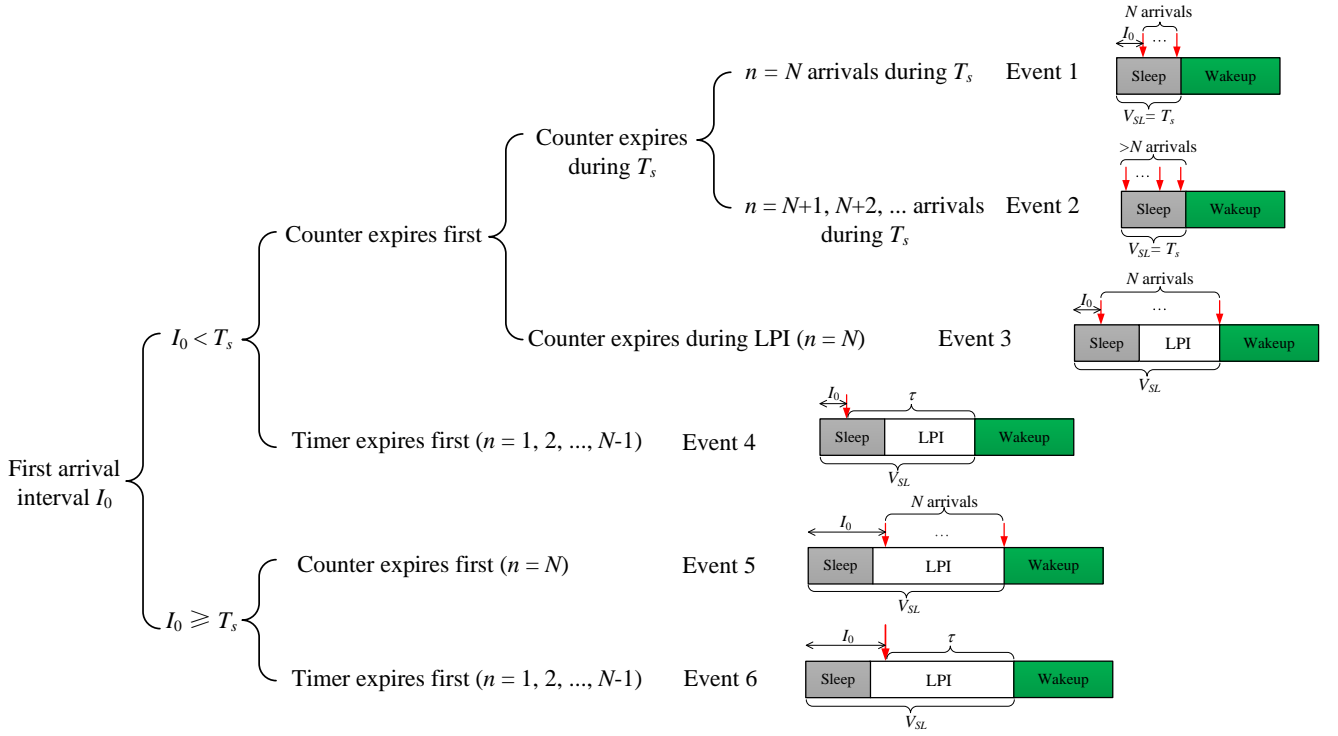


Fig. 2. Arrival event tree during V_{SL} .

Lemma 1. *The distribution of the number of arrivals during V_{SL} is given by equation (1).*

Proof: Let I_0 be the time interval from the beginning of the vacation to the time when the first frame arrives, and I_i be the inter-arrival time between the i th arrival and the $(i+1)$ th arrival during the vacation, where $i = 1, 2, \dots$. As Fig. 2 shows, there are six mutually exclusive arrival events that could occur during V_{SL} . They can be classified into the following four cases:

1. $n = 0$

According to the BTR strategy, it is impossible that the link wakes up without any arrival, therefore

$$a_0 = 0, \quad (2)$$

which implies that there is at least one arrival during V_{SL} .

2. $n = 1, 2, \dots, N-1$

Regardless if the first frame arrives before or after the end of the Sleep period, that is, $I_0 \leq T_s$ or $I_0 > T_s$, if the V_{SL} terminates when the timer expires, then the number of arrivals must be less than N . In Fig. 2, the timer expires

in Events 4 and 6, thus we have

$$\begin{aligned} a_n &= \Pr\{I_0 \leq T_s, n-1 \text{ arrivals in an interval } \tau\} \\ &\quad + \Pr\{I_0 > T_s, n-1 \text{ arrivals in an interval } \tau\} \\ &= \Pr\{n-1 \text{ arrivals in an interval } \tau\} \\ &= e^{-\lambda\tau} \frac{(\lambda\tau)^{n-1}}{(n-1)!}, \end{aligned} \quad (3)$$

for $n = 1, 2, \dots, N-1$.

3. $n = N+1, N+2, \dots$

The number of arrivals n during V_{SL} can be larger than N only if they all arrived during Sleep period T_s , which occurs in Event 2. It follows that

$$a_n = \Pr\{n \text{ arrivals in the interval } T_s\} = e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!}, \quad (4)$$

for $n = N+1, N+2, \dots$.

4. $n = N$

In Events 1, 3 and 5 shown in Fig. 2, V_{SL} is ended with exactly N frames in the buffer. In Event 1, there are N arrivals during Sleep period T_s , and the counter triggers the Wakeup immediately at the end of Sleep period. In Event 3, the first frame arrives during Sleep period T_s , that is, $I_0 < T_s$, and N frames arrive after the Sleep but before

$$a_n = \Pr\{n \text{ arrivals during } V_{SL}\} = \begin{cases} 0, & n = 0 \\ e^{-\lambda\tau} \frac{(\lambda\tau)^{n-1}}{(n-1)!}, & n = 1, 2, \dots, N-1 \\ \sum_{n=0}^N e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} - \sum_{n=1}^{N-1} e^{-\lambda\tau} \frac{(\lambda\tau)^{n-1}}{(n-1)!}, & n = N \\ e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!}, & n = N+1, N+2, \dots \end{cases} \quad (1)$$

$I_0 + \tau$. In Event 5, the first frame arrives after T_s , that is, $I_0 > T_s$, and N frames arrive before $I_0 + \tau$. Given $\sum_{n=0}^{\infty} a_n = 1$, from (3) and (4), we have

$$\begin{aligned} a_N &= Pr\{N \text{ arrivals in the interval } T_s\} \\ &\quad + Pr\{I_0 \leq T_s, T_s - T_0 < I_1 + \dots + I_{N-1} \leq \tau\} \\ &\quad + Pr\{I_0 > T_s, I_1 + \dots + I_{N-1} \leq \tau\} \\ &= 1 - \sum_{n=1}^{N-1} e^{-\lambda\tau} \frac{(\lambda\tau)^{n-1}}{(n-1)!} - \sum_{n=N+1}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \\ &= \sum_{n=0}^N e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} - \sum_{n=1}^{N-1} e^{-\lambda\tau} \frac{(\lambda\tau)^{n-1}}{(n-1)!}. \end{aligned} \quad (5)$$

Let b_n be the probability that there are n arrivals during Wakeup period T_w , we have

$$b_n = Pr\{n \text{ arrivals during } T_w\} = e^{-\lambda T_w} \frac{(\lambda T_w)^n}{n!}, \quad (6)$$

for $n = 0, 1, \dots$. From Lemma 1 and (6), the generating functions of a_n and b_n are respectively given as follows.

$$\begin{aligned} A(z) &= \sum_{n=0}^{\infty} a_n z^n \\ &= \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} (z^N - z^n) \\ &\quad - \sum_{n=0}^{N-2} e^{-\lambda\tau} \frac{(\lambda\tau)^n}{n!} (z^N - z^{n+1}) + e^{-\lambda T_s (1-z)} \end{aligned} \quad (7)$$

and

$$B(z) = \sum_{n=0}^{\infty} b_n z^n = e^{-\lambda T_w} \sum_{n=0}^{\infty} \frac{(\lambda T_w z)^n}{n!} = e^{-\lambda T_w (1-z)} \quad (8)$$

Since the number of arrivals during vacation period V is the sum of arrivals during V_{SL} and that of T_w , the probability that there are n arrivals during vacation period V is the convolution of a_n and b_n given as follows:

$$h_n = \sum_{k=0}^n a_{n-k} b_k \quad (9)$$

Thus, the generating function of h_n is given by $H(z) = A(z)B(z)$, and we immediately obtain the mean number of arrivals during a vacation period as follows:

$$\begin{aligned} \bar{\alpha} &= H'(1) \\ &= \lambda(T_w + T_s) + \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} (N - n) \\ &\quad - \sum_{n=0}^{N-2} e^{-\lambda\tau} \frac{(\lambda\tau)^n}{n!} [N - (n+1)]. \end{aligned} \quad (10)$$

Furthermore, it follows from Little's Law that the mean

vacation time under the $\tau \& N$ policy is given by

$$\begin{aligned} \bar{V} &= \frac{\bar{\alpha}}{\lambda} = \frac{H'(1)}{\lambda} \\ &= T_s + \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \left(\frac{N - n}{\lambda} \right) \\ &\quad - \sum_{n=0}^{N-2} e^{-\lambda\tau} \frac{(\lambda\tau)^n}{n!} \left(\frac{N - n - 1}{\lambda} \right) + T_w. \end{aligned} \quad (11)$$

Recall that the τ policy is a $\tau \& N$ policy with $N \rightarrow \infty$ and the N policy is a $\tau \& N$ policy with $\tau \rightarrow \infty$. Thus, letting $N \rightarrow \infty$, the mean vacation time under the τ policy can be derived from (11) as follows:

$$\bar{V}_\tau = \lim_{N \rightarrow \infty} \bar{V} = \frac{1}{\lambda} + \tau + T_w, \quad (12)$$

which includes three components: (1) the expected time from the beginning of the vacation period to the first arrival time, (2) the duration of the timer, and (3) the Wakeup period. Similarly, $\tau \rightarrow \infty$ results in the mean vacation time under the N policy:

$$\bar{V}_N = \lim_{\tau \rightarrow \infty} \bar{V} = T_s + \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \left(\frac{N - n}{\lambda} \right) + T_w. \quad (13)$$

Since the Sleep period T_s is very small, we can ignore the probability that there are at least $N - 1$ arrivals during T_s , that is, $\sum_{n=N-1}^{\infty} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \approx 0$, then we have:

$$\begin{aligned} \bar{V}_N &= T_s + \frac{N}{\lambda} \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} + T_w \\ &\quad - T_s \sum_{n=0}^{N-2} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \approx \frac{N}{\lambda} + T_w, \end{aligned} \quad (14)$$

which indicates that the Wakeup is triggered by the N th arrival in the N policy. Equations (11) through (14) demonstrate that the mean vacation time is determined by timer τ and counter N . In particular, \bar{V}_τ and \bar{V}_N are proportional to τ and N , respectively.

B. Power Efficiency

The design of the EEE protocol aims to maximize power efficiency, which is defined as the percentage of energy the EEE protocol can save. As we previously mentioned in this section, the power consumption during LPI periods is φ_l and that during Sleeps, Wakeups, and busy periods it is φ_h , and $\varphi_l = 10\% \varphi_h$. Let ρ be the offered load, that is, $\rho = \lambda \bar{X}$, then the mean cycle time is given by $\bar{C} = \bar{V} / (1 - \rho)$. Because the mean time of the LPI period in a cycle is $\bar{V} - T_s - T_w$, the mean power consumption of the EEE system is given by:

$$\varphi_{EEE} = \frac{(\bar{V} - T_s - T_w) \varphi_l + (\bar{C} - \bar{V} + T_s + T_w) \varphi_h}{\bar{C}}. \quad (15)$$

Without the EEE protocol, power consumption of an interface is a constant φ_h . It follows that the power efficiency is given

by

$$\begin{aligned}\eta &= \frac{\varphi_h - \varphi_{EEE}}{\varphi_h} \\ &= \frac{(\bar{V} - T_s - T_w)(\varphi_h - \varphi_l)}{\bar{V}/(1-\rho)\varphi_h} \\ &= \left(1 - \frac{T_s + T_w}{\bar{V}}\right) \cdot \frac{(1-\rho)(\varphi_h - \varphi_l)}{\varphi_h}. \quad (16)\end{aligned}$$

This expression clearly demonstrates that power efficiency η increases with \bar{V} for a given traffic load ρ . Moreover, when $n \rightarrow \infty$, we can obtain the power efficiency of the τ policy:

$$\eta_\tau = \lim_{N \rightarrow \infty} \eta = \left(1 - \frac{T_s + T_w}{\frac{1}{\lambda} + \tau + T_w}\right) \cdot \frac{(1-\rho)(\varphi_h - \varphi_l)}{\varphi_h}. \quad (17)$$

Similarly, when $\tau \rightarrow \infty$, we can obtain the following power efficiency of the N policy:

$$\begin{aligned}\eta_N &= \lim_{\tau \rightarrow \infty} \eta \\ &= \left(1 - \frac{T_s + T_w}{T_s + \sum_{n=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^n}{n!} \left(\frac{N-n}{\lambda}\right) + T_w}\right) \cdot \frac{(1-\rho)(\varphi_h - \varphi_l)}{\varphi_h} \\ &\approx \left(1 - \frac{T_s + T_w}{\frac{N}{\lambda} + T_w}\right) \cdot \frac{(1-\rho)(\varphi_h - \varphi_l)}{\varphi_h}, \quad (18)\end{aligned}$$

where the approximation is obtained by ignoring the probability that there are at least $N - 1$ arrivals during T_s .

III. P-K FORMULA OF MEAN DELAY

The mean delay of a traditional M/G/1 queueing system with vacation is given by the following well-known P-K formula:

$$D = \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{\bar{V}^2}{2\bar{V}} + \bar{X}, \quad (19)$$

where \bar{V}^2 is the second moment of the vacation time. Ref. [21] states that this formula can be applied to different scenarios and points out “the length of a vacation interval need not be independent of the customers arrival and service times.” If this is the case, the mean delay can be readily obtained once the distribution of the vacation time is determined. In an EEE system, however, the vacation time is completely governed by the arrival process. In contrast to the above comment on equation (19), the following two counter examples show that the above P-K formula is invalid in a system controlled by the EEE protocol:

1. In the Appendix, we show that the following classical relationship between the number of arrivals in a vacation time and the distribution of vacation time V [24] does not hold in EEE systems:

$$H(z) = V^*(\lambda - \lambda z), \quad (20)$$

where $V^*(s)$ is the generating function of the vacation time distribution.

2. The counter example provided in the Appendix shows that (19) is invalid for EEE systems even if the exact vacation time distribution is known.

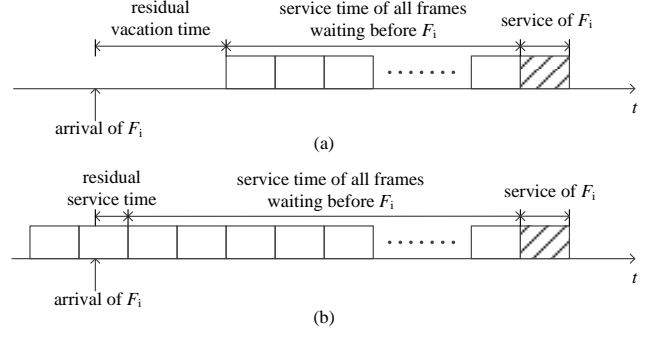


Fig. 3. Frame F_i arrives during (a) a vacation period (b) a busy period.

As we explain in the Appendix, both of these two counter examples are induced by the dependency between the vacation time and the arrival process. In this subsection, we derive the appropriate mean delay formula for EEE systems.

Consider the i th arrival frame, denoted as F_i , in cycle C . Frame F_i may arrive during the busy period of C or the vacation period of C . Before frame F_i receives service, it waits in the buffer for the completion of the current service period or current vacation period, and then for the services of all frames waiting in the buffer ahead of F_i . Let R_i be the residual time, either service or vacation, of frame F_i . Following the same argument Ref. [21] states, we have:

$$D = \frac{\bar{R}}{1-\rho} + \bar{X}, \quad (21)$$

in which the mean residual time $\bar{R} = E[R_i]$ is the key to derive the P-K formula. As we explain in the Appendix, similar to the vacation time, the residual vacation time is related to the arrival process. Let V_n denote a vacation period terminated with n arrivals, and P_n be the probability that frame F_i arrives in a V_n . We need the following lemma to derive the P-K formula.

Lemma 2. *If a frame arrives during a vacation period, then the probability that the frame arrives in a V_n is given by:*

$$P_n = \frac{nh_n}{H'(1)}. \quad (22)$$

Proof: Suppose the EEE system undergoes k_n vacation periods V_n , for $n = 1, 2, \dots$, in the time interval $[0, T]$. Then the probability h_n that a vacation period is a V_n is defined by:

$$h_n = \lim_{T \rightarrow \infty} \frac{k_n}{\sum_{n=1}^{\infty} k_n}. \quad (23)$$

Thus, the conditional probability P_n that a frame arrives in a V_n is given by:

$$P_n = \lim_{T \rightarrow \infty} \frac{nk_n}{\sum_{n=1}^{\infty} nk_n} = \frac{nh_n}{\sum_{n=1}^{\infty} nh_n} = \frac{nh_n}{H'(1)}. \quad (24)$$

For a given traffic load ρ , the following theorem shows that the mean delay of an EEE system is completely governed by h_n , which is determined by the BTR strategy of EEE protocols. ■

Theorem 1. *The mean delay of EEE systems is given by:*

$$D = \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{H''(1)}{2\lambda H'(1)} + \bar{X}. \quad (25)$$

Proof: As Fig. 3 illustrates, a frame F_i may experience a residual time waiting for the completion of a service or a vacation, depending on whether it arrives during a busy period or a vacation period. Define the following indicator variable:

$$\xi = \begin{cases} 0, & \text{if a frame arrives during a vacation period} \\ 1, & \text{if a frame arrives during a busy period,} \end{cases}$$

The mean residual time can then be expressed as follows:

$$\begin{aligned} \bar{R} &= E[R_i|\xi=0] \times Pr\{\xi=0\} + E[R_i|\xi=1] \times Pr\{\xi=1\} \\ &= E[R_i|\xi=0] \times (1-\rho) + E[R_i|\xi=1] \times \rho. \end{aligned} \quad (26)$$

The conditional expectation $E[R_i|\xi=1]$ in (26) can be solved by using the graphic method described in [21] and expressed as follows:

$$E[R_i|\xi=1] = \frac{1}{2\rho} \lambda \bar{X}^2. \quad (27)$$

The mean residual vacation time can be obtained from the following expression of the conditional expected value:

$$E[R_i|\xi=0] = \sum_{n=1}^{\infty} E[R_i|\xi=0, \text{frame } i \text{ arrives in a } V_n] P_n. \quad (28)$$

Let Q_i be the number of frames that arrive during time period R_i , or equivalently, the queue length behind the i th frame in the buffer when the vacation period terminates. Applying Little's Law to (28), we have:

$$\begin{aligned} \lambda E[R_i|\xi=0] &= \sum_{n=1}^{\infty} \lambda E[R_i|\xi=0, \text{frame } i \text{ arrives in a } V_n] P_n \\ &= \sum_{n=1}^{\infty} E[Q_i|\xi=0, \text{frame } i \text{ arrives in a } V_n] P_n \\ &= \sum_{n=1}^{\infty} \left[\frac{(n-1) + (n-2) + \dots + 1 + 0}{n} \right] \frac{n h_n}{H'(1)} \\ &= \frac{1}{2H'(1)} \sum_{n=1}^{\infty} n(n-1) h_n \\ &= \frac{H''(1)}{2H'(1)}. \end{aligned} \quad (29)$$

The theorem is established by combining (21), (26), (27), and (29). ■

If the vacation time is independent of the arrival process in an M/G/1 queue with vacations, then the relation $H(z) = V^*(\lambda - \lambda z)$ holds. We have

$$H'(1) = V^{*'}(\lambda - \lambda z)|_{z=1} = \lambda \bar{V} \quad (30)$$

and

$$H''(1) = V^{*''}(\lambda - \lambda z)|_{z=1} = \lambda^2 \bar{V}^2. \quad (31)$$

Substituting (30) and (31) into (25), we obtain the classical P-K formula of mean delay (19) again. Thus, the formula (25) given in Theorem 1 is more general than the classical P-K formula (19). The later is a special case of (25) when the relation $H(z) = V^*(\lambda - \lambda z)$ holds.

Substituting the generating function $H(z)$ into (25), we can obtain the mean delay of the τ & N policy:

$$D = \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{A}{2\lambda B} + \bar{X} \quad (32)$$

where

$$\begin{aligned} A &= (\lambda T_w + \lambda T_s)^2 + \sum_{k=0}^{N-1} \left\{ e^{-\lambda T_s} \frac{(\lambda T_s)^k}{k!} [2\lambda T_w(N-k) \right. \\ &\quad \left. + N(N-1) - k(k-1)] \right\} - \sum_{k=0}^{N-2} \left\{ e^{-\lambda \tau} \frac{(\lambda \tau)^k}{k!} \right. \\ &\quad \left. \times [2\lambda T_w(N-k-1) + N(N-1) - k(k+1)] \right\} \end{aligned}$$

and

$$\begin{aligned} B &= \lambda(T_w + T_s) + \sum_{k=0}^{N-1} e^{-\lambda T_s} \frac{(\lambda T_s)^k}{k!} (N-k) \\ &\quad - \sum_{k=0}^{N-2} e^{-\lambda \tau} \frac{(\lambda \tau)^k}{k!} (N-k-1). \end{aligned}$$

Letting $N \rightarrow \infty$, we obtain the mean delay of the τ policy:

$$D_\tau = \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{[\lambda(\tau + T_w)]^2 + 2\lambda(\tau + T_w)}{2\lambda[1 + \lambda(\tau + T_w)]} + \bar{X}. \quad (33)$$

Similarly, $\tau \rightarrow \infty$ yields the mean delay of the N policy which is shown in equation (34) where the approximation is obtained by ignoring the probability that more than $N-1$ frames arrive within the Sleep period T_s .

IV. POWER EFFICIENCY AND DELAY TRADEOFF

In this section, we study the performance of EEE systems in terms of power efficiency and mean delay through the results obtained in Section II and Section III. We demonstrate the tradeoff between different parameters, which in turn provides the principle to optimize the design of the EEE protocol. Our goal is to find the rules to select appropriate values for parameters τ and N with regards to the performances of the EEE protocol. In the following analysis, we assume that the average frame size is 1250 bytes, and thus the average frame transmission rate is 1 frame/ μ s.

$$\begin{aligned} D_N &= \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{(\lambda T_w + \lambda T_s)^2 + e^{-\lambda T_s} \sum_{k=0}^{N-1} \frac{(\lambda T_s)^k}{k!} [2\lambda T_w(N-k) + N(N-1) - k(k-1)]}{2\lambda[\lambda(T_w + T_s) + e^{-\lambda T_s} \sum_{k=0}^{N-1} \frac{(\lambda T_s)^k}{k!} (N-k)]} + \bar{X} \\ &\approx \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{(N + \lambda T_w)^2 - N}{2\lambda(N + \lambda T_w)} + \bar{X}. \end{aligned} \quad (34)$$

A. Timer versus Counter

The key parameters of the EEE protocol are timer threshold τ and counter threshold N . The analytical results presented in the previous section reveal that the vacation time is governed by the arrival process. Thus, the behavior of an EEE system can be characterized by the inter-relationship between these two parameters and frame arrival rate λ .

In the $\tau\&N$ policy, the timer and the counter are initialized upon the first arrival during the vacation. According to Little's Law, the mean vacation time \bar{V} given by (11) can be approximately rewritten as follows:

$$\bar{V} \approx \min\{\bar{V}_\tau, \bar{V}_N\} = \min\left\{\frac{1}{\lambda} + \tau, \frac{N}{\lambda}\right\} + T_w. \quad (35)$$

Therefore, depending on the frame arrival rate λ , the Wakeup could be triggered by the timer or the counter. The following are possible scenarios:

1. If the arrival rate is small, say $\lambda < \frac{N-1}{\tau}$, then $\bar{V} \approx \frac{1}{\lambda} + \tau + T_w$ implies that the Wakeup is most likely triggered by the timer. In this case, the $\tau\&N$ policy acts similar to the τ policy, which ensures that the residual vacation time of a frame arrived during the vacation period is bounded by $\tau + T_w$.
2. If the arrival rate is large, say $\lambda > \frac{N-1}{\tau}$, then $\bar{V} \approx \frac{N}{\lambda} + T_w$ implies that the Wakeup is mainly triggered by the counter. In this case, the $\tau\&N$ policy performs as the N policy, such that the backlogged queue length at the end of vacation can be bounded. Therefore, the queueing delay induced by the vacation period can also be bounded.
3. For a moderate arrival rate $\lambda \approx \frac{N-1}{\tau}$, the Wakeup could be triggered by the timer or the counter with almost the same probability.

Presumably, the instantaneous arrival rate $\lambda(t)$ may fluctuate around the steady state rate $\lambda = \lim_{t \rightarrow \infty} \lambda(t)$ over time t . The above property indicates that the $\tau\&N$ policy is able to adapt to the fluctuations of the arrival rate, and it will strike a balance between τ policy and N policy. This property is particularly useful in the face of bursty arrival traffic.

The power efficiency and the mean delay versus the frame arrival rate λ , where $\tau = 30\mu s$ and $N = 11$, are depicted in Fig. 4 which plots (16), (17), and (18) in Fig. 4(a), and (32), (33), and (34) in Fig. 4(b). The simulation results perfectly agree with our analytical predictions in power efficiency and mean delay. Power efficiency η is proportional with \bar{V} as we explained in Section II-B. Therefore, similar to (35), the power efficiency η can be approximately expressed as follows:

$$\begin{aligned} \eta &\approx \min\{\eta_\tau, \eta_N\} \\ &= \min\left\{1 - \frac{T_s + T_w}{\frac{1}{\lambda} + \tau + T_w}, 1 - \frac{T_s + T_w}{\frac{N}{\lambda} + T_w}\right\} \frac{(1 - \rho)(\varphi_h - \varphi_l)}{\varphi_h}. \end{aligned} \quad (36)$$

Accordingly, we obtain the following approximation of the mean delay D given by (32):

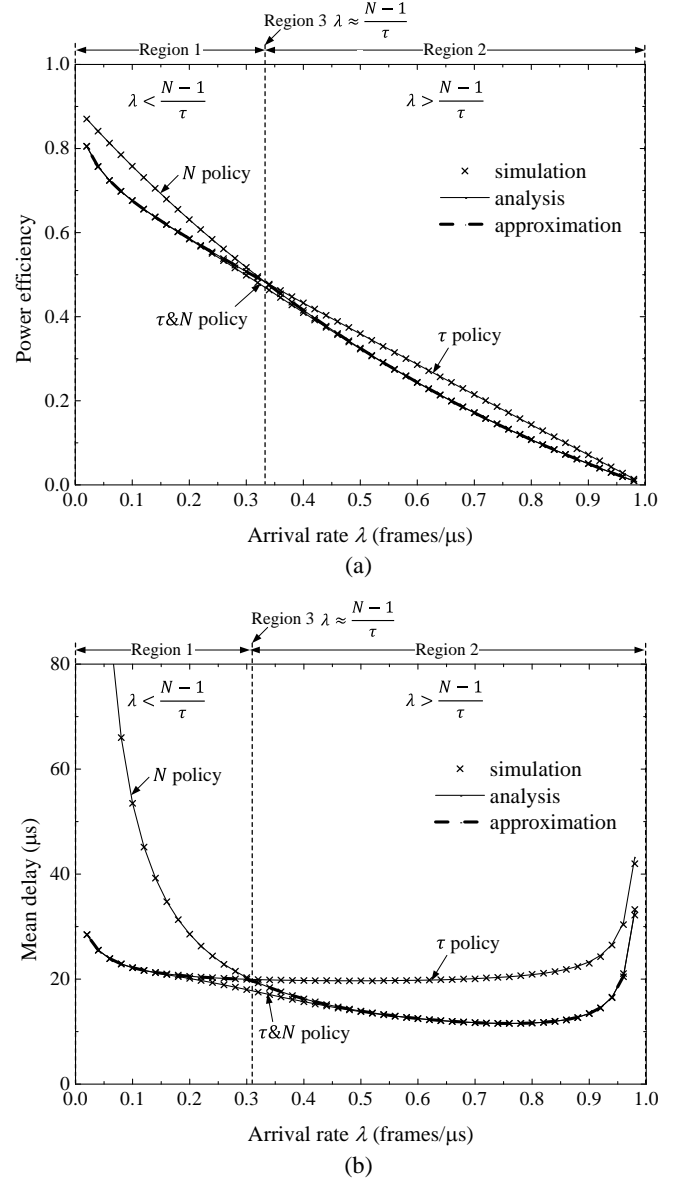


Fig. 4. Performance evaluation: (a) power efficiency and (b) mean delay vs. λ , where $\tau = 30\mu s$ and $N = 11$.

$$\begin{aligned} D &\approx \min\{D_\tau, D_N\} \\ &= \min\left\{\frac{[\lambda(\tau + T_w)]^2 + 2\lambda(\tau + T_w)}{2\lambda[1 + \lambda(\tau + T_w)]}, \frac{(N + \lambda T_w)^2 - N}{2\lambda(N + \lambda T_w)}\right\} \\ &\quad + \frac{\lambda \bar{X}^2}{2(1 - \rho)} + \bar{X}. \end{aligned} \quad (37)$$

As Fig. 4 shows, the approximations given by (36) and (37) are quite accurate for practical applications. Also, despite the power efficiencies η , η_τ , and η_N in three different regions are all close to each other, the discrepancy among the mean delays D , D_τ , and D_N can be quite substantial. For example, $D_N = 54\mu s$ while $D_\tau = D = 22\mu s$ when $\lambda = 0.1$ frames/ μs , and $D_\tau = 21\mu s$ while $D_N = D = 12\mu s$ when $\lambda = 0.8$ frames/ μs .

Since Ethernet traffic is typically bursty, the $\tau\&N$ policy

adapts to traffic fluctuations. As we explained above, the N policy suffers from a large delay in region $\lambda < (N-1)/\tau$, since λ is small and it may take a long time for the counter to reach N . In contrast, the τ policy faces a large delay in region $\lambda > (N-1)/\tau$, because the large rate λ incurs a large number of backlogged frames during time τ . As a compromise, the $\tau \& N$ policy can avoid large delays in these two side regions if parameters τ and N are selected according to the following rule:

EEE 1. For a given steady state traffic rate λ , the selection of parameters τ and N should comply with the following condition:

$$\frac{N-1}{\tau} = \lambda. \quad (38)$$

B. Power Efficiency versus Mean Delay

In this subsection, we investigate the power efficiency η and the mean delay D of the $\tau \& N$ policy under the assumption that (38) of the selection rule EEE 1 is observed. For a given arrival rate $\lambda = 1/3$ frames/ μs , the power efficiency η is plotted as a function of N in Fig. 5(a), from which we can see that η increases with N and finally converges to a constant. As the expression (16) demonstrates, the power efficiency η increases with the mean vacation time \bar{V} , which increases with τ and N . In particular, if \bar{V} goes to infinity with τ and N , the ratio $\frac{T_w + T_s}{\bar{V}}$ approaches 0, meaning that the overhead, including the Sleep time and the Wakeup time, is negligible if the LPI period is sufficiently long. In this case, the power efficiency reaches the following maximal value:

$$\eta^* = \lim_{\bar{V} \rightarrow \infty} = \frac{(1-\rho)(\varphi_h - \varphi_l)}{\varphi_h} \quad (39)$$

The mean delay D is almost linearly proportional to τ and N , as Fig. 5(b) shows. Intuitively, if parameter τ and N are too large, then a large number of frames that arrive during the vacation time would have to wait for a long time before the timer expires or the counter reaches the threshold N . Furthermore, the large number of backlogged frames will also affect the queueing delay of the frames.

The results in Fig. 5 indicate that excessive large τ and N degrade delay performance while marginally enhancing the power efficiency. Under condition $\frac{N-1}{\tau} = \lambda$ of the selection rule EEE 1, we obtain the following mean delay as a function of the power efficiency from (18) and (34):

$$D \approx \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{T_s + T_w}{2(1-\frac{\eta}{\eta^*})} - \frac{T_s + T_w \frac{\eta}{\eta^*}}{2\lambda(T_s + T_w)} + \bar{X}. \quad (40)$$

Taking the derivative of (40) with respect to η , we have:

$$\frac{dD}{d\eta} \approx \frac{T_s + T_w}{2\eta^*(1-\frac{\eta}{\eta^*})^2} - \frac{T_w}{2\lambda\eta^*(T_s + T_w)}. \quad (41)$$

Eq. (40) and Eq. (41) demonstrate that the power efficiency of the EEE protocol is improved at the expense of increasing mean delay. When power efficiency η is small, it can be significantly improved with a small increase of delay D , while the delay D skyrockets to infinity as η approaches η^* . For

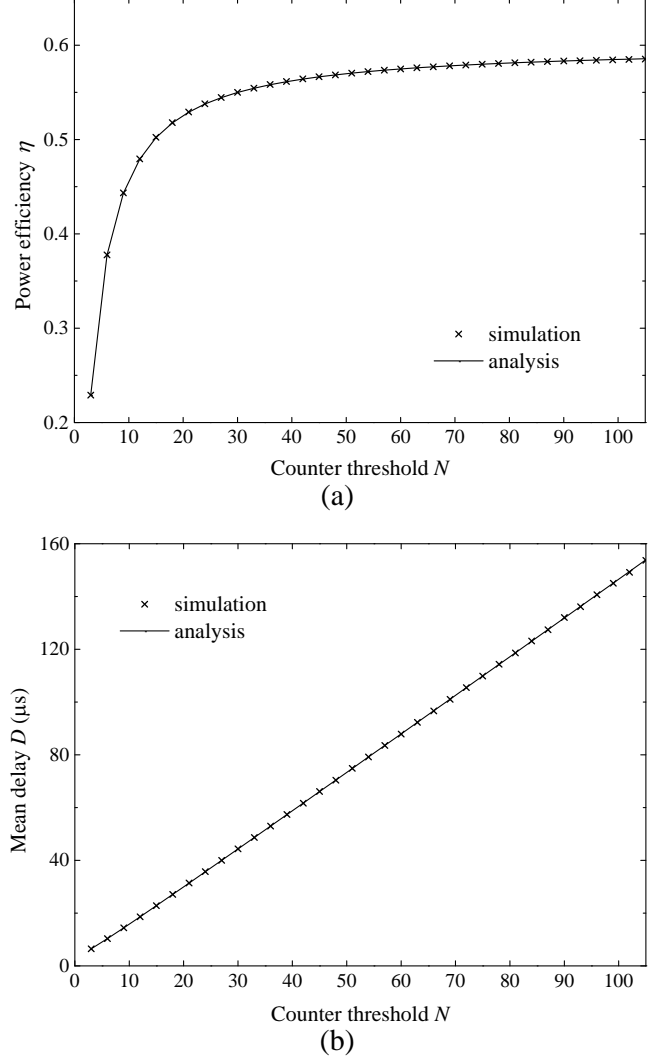


Fig. 5. Performance evaluation: (a) power efficiency and (b) mean delay versus N , where $\frac{N-1}{\tau} = \lambda$ and $\lambda = 1/3$ frames/ μs .

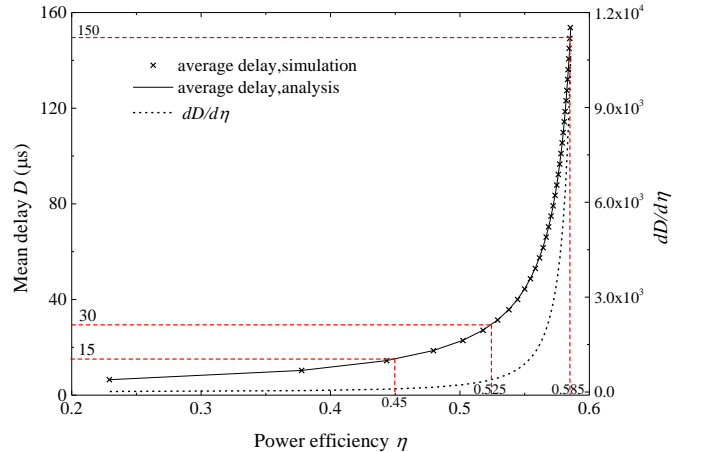


Fig. 6. Mean delay versus power efficiency when $\lambda = 1/3$ frames/ μs .

example, as Fig. 6 shows, the mean delay D is doubled when η increases from 0.45 to 0.525, while it expands five times when η only slightly increases from 0.525 to 0.585. Thus, our second rule to select the parameters of the EEE protocol is given as follows:

EEE 2. *Parameter N of the EEE protocol can be selected from (34) according to a given mean delay requirement D .*

According to the above two selection rules, counter threshold N can be derived from Eq. (34) when the delay requirement is given. Then timer threshold τ is determined by rule EEE 1 and the corresponding power efficiency is given by Eq. (40). Table I lists the parameter selection procedures of EEE systems under different arrival rates. Here, the delay requirements are expressed in terms of the mean delay of the EEE system with FTR strategy as a reference.

For the FTR strategy, the power efficiency and mean delay can be obtained from (16) and (25), respectively. The first and the second moments of h_n are respectively given by

$$H'(1) = \lambda(T_s + T_w) + e^{-\lambda T_s},$$

and

$$H''(1) = [\lambda(T_s + T_w)]^2 + 2\lambda T_w e^{-\lambda T_s}.$$

Assuming the service rate is 1 frame/ μs for the FTR strategy, we obtain the following mean delay and power efficiency with respect to different traffic loads:

- (1) $\lambda_1 = 1/5$ frames/ μs , $D_1 = 5.0261\mu s$, $\eta_1 = 0.1990$;
- (2) $\lambda_2 = 1/3$ frames/ μs , $D_2 = 5.0380\mu s$, $\eta_2 = 0.0810$;
- (3) $\lambda_3 = 3/5$ frames/ μs , $D_3 = 5.4609\mu s$, $\eta_3 = 0.0139$.

TABLE I
PARAMETERS SELECTION UNDER DIFFERENT ARRIVAL RATES AND
DELAY REQUIREMENTS

λ (frames/ μs)	Strategy	D (μs)	η	N	τ (μs)
$\lambda_1 = 1/5$	FTR	D_1	η_1	1	0
	BTR	$1.23D_1$	$1.53\eta_1$	2	5
		$2.03D_1$	$2.36\eta_1$	4	15
		$5.20D_1$	$3.12\eta_1$	11	50
		$9.91D_1$	$3.35\eta_1$	21	100
		$19.49D_1$	$3.48\eta_1$	41	200
$\lambda_2 = 1/3$	FTR	D_2	η_2	1	0
	BTR	$1.09D_2$	$1.76\eta_2$	2	3
		$2.05D_2$	$4.66\eta_2$	6	15
		$5.09D_2$	$6.33\eta_2$	17	48
		$10.23D_2$	$6.88\eta_2$	35	102
		$20.06D_2$	$7.14\eta_2$	69	204
$\lambda_3 = 3/5$	FTR	D_3	η_3	1	0
	BTR	$1.01D_3$	$1.62\eta_3$	2	1.67
		$1.99D_3$	$15.96\eta_3$	10	15
		$5.04D_3$	$22.27\eta_3$	31	50
		$9.92D_3$	$24.13\eta_3$	65	105
		$20.23D_3$	$25.03\eta_3$	133	220

λ : arrival rate, D : mean delay, η : power efficiency.

V. CONCLUSION

This paper presents an analytical model for the BTR strategy of 10GBase-T Energy Efficient Ethernet and derives the power efficiency and mean delay of the system. The proposed model is the first approach that can dispose of the dependency between the vacation time and the arrival process as well as the parameters of the BTR strategy. In our model, we start with the distribution of the number of arrivals during a vacation time based on an event tree, and then derive the power efficiency and a generalized P-K formula of the mean delay for EEE systems.

Our analysis shows that the counter and the timer play different roles in performance guarantees and compensate each other to adapt to traffic fluctuations. Therefore, the τ & N policy can better adapt to the traffic on Ethernet networks, which typically are bursty. Based on these properties, we provide the rules to select appropriate values for parameters τ and N . The methodology developed in this paper can be generalized and applied to the analysis of queueing models with vacation time that is governed by the arrival process.

APPENDIX A

FAILURE OF THE CLASSICAL P-K FORMULA IN THE VACATION MODEL OF EEE PROTOCOL

It is well-known that, with a Poisson arrival process, the relation

$$H(z) = V^*(\lambda - \lambda z)$$

holds in the classical M/G/1 queue with vacation time, where $H(z)$ is the z transform of the distribution h_n of the number of the arrivals during the vacation and $V^*(s)$ is the Laplace transform of the vacation time distribution $v(x)$. However, this relation is invalid in the vacation model of the EEE protocol, where the vacation time is regulated by the arrival process. In the following, we take the τ policy as an example to demonstrate this point.

As Fig. 7 shows, the vacation time of the τ policy consists of three parts: the time from the beginning of the vacation to the first arrival I_0 , the LPI time τ , and the Wakeup period T_w . As τ and T_w are constants, the probability distribution function (PDF) of vacation time is given by:

$$v(x) = \lambda e^{-\lambda(x-\tau-T_w)}, \quad x \geq \tau + T_w. \quad (42)$$

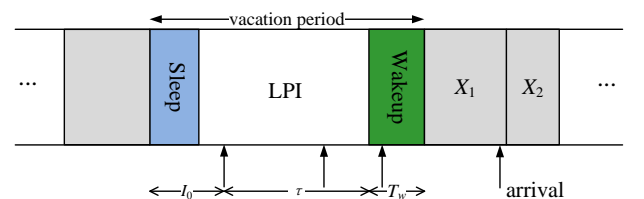


Fig. 7. Illustration of the τ policy.

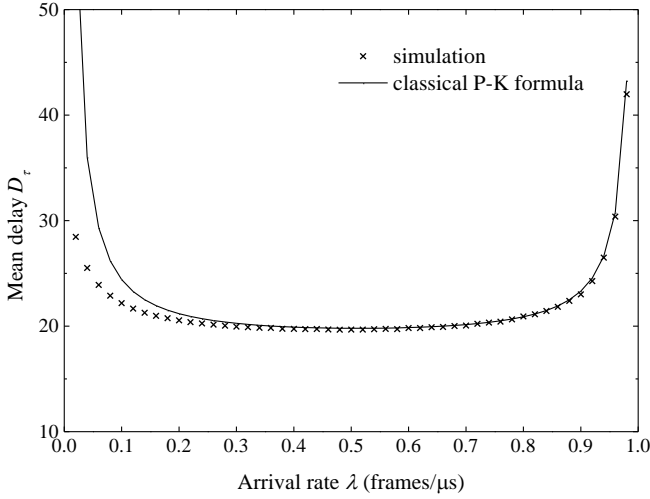


Fig. 8. Validation of the classical P-K formula, where $\tau = 30\mu s$.

Taking the Laplace transform, we have:

$$\begin{aligned} V^*(s) &= \int_0^\infty e^{-sx} v(x) dx \\ &= \lambda \int_{\tau+T_w}^\infty e^{-sx} e^{-\lambda(x-\tau-T_w)} dx \\ &= \frac{\lambda}{\lambda+s} e^{-s(\tau+T_w)}. \end{aligned} \quad (43)$$

On the other hand, the distribution of the number of arrivals during vacation time h_n is given by:

$$h_n = e^{-\lambda(\tau+T_w)} \frac{[\lambda(\tau+T_w)]^{n-1}}{(n-1)!}, \quad (n \geq 1). \quad (44)$$

and the generating function of h_n can be expressed as follows:

$$H(z) = \sum_{n=0}^\infty h_n z^n = z e^{-\lambda(1-z)(\tau+T_w)}. \quad (45)$$

Clearly, the equality $H(z) = V^*(\lambda - \lambda z)$ does not hold in the vacation model of the EEE protocol.

Next, we examine whether the P-K formula (19) for the traditional M/G/1 queue with vacation time can still be applied to the vacation model of the EEE protocol. From (43), the first and the second moment of the vacation time are respectively given as follows:

$$\bar{V} = -V^*(0) = \frac{1}{\lambda} + \tau + T_w, \quad (46)$$

$$\bar{V}^2 = V^{*''}(0) = \frac{2}{\lambda^2} + (\tau + T_w)^2. \quad (47)$$

Substituting (46) and (47) into the classical P-K formula (19), we obtain:

$$\begin{aligned} D &= \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{\bar{V}^2}{2\bar{V}} + \bar{X} \\ &= \frac{\lambda \bar{X}^2}{2(1-\rho)} + \frac{\frac{2}{\lambda^2} + \frac{2(\tau+T_w)}{\lambda} + (\tau+T_w)^2}{2(\frac{1}{\lambda} + \tau + T_w)} + \bar{X}. \end{aligned} \quad (48)$$

We verify the above result (48) by simulation. Fig. 8 shows that the simulation results are always lower than the

numerical results of equation (48). This discrepancy reveals the difference between the classical M/G/1 queue with vacation time and the vacation model of the EEE protocol. In the former system, the vacation time is independent of the arrival process. For a packet that arrived in a vacation period, the density of the residual vacation time is given by [24]:

$$\hat{f}_v(x) = \frac{1 - F_v(x)}{\bar{V}}, \quad (49)$$

where $F_v(x)$ is the distribution of the vacation time V . However, in an EEE protocol with the τ policy, the residual vacation time of the first arrival is deterministic and equals $\tau + T_w$. Therefore, the density of the residual vacation time in the model of EEE protocol is no longer given by (49). As Fig. 8 shows, the discrepancy is more significant when the arrival rate λ is smaller because fewer packets arrive in a vacation time.

REFERENCES

- [1] M. Gupta and S. Singh, "Greening of the Internet," in *Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, SIGCOMM '03*, (New York, NY, USA), pp. 19–26, ACM, 2003.
- [2] R. Bolla, R. Bruschi, F. Davoli, and F. Cucchietti, "Energy efficiency in the future Internet: A survey of existing approaches and trends in energy-aware fixed network infrastructures," *IEEE Communications Surveys Tutorials*, vol. 13, pp. 223–244, Second 2011.
- [3] P. J. Winzer, "Beyond 100G Ethernet," *IEEE Communications Magazine*, vol. 48, pp. 26–30, July 2010.
- [4] P. Reviriego, K. Christensen, J. Rabanillo, and J. A. Maestro, "An initial evaluation of Energy Efficient Ethernet," *IEEE Communications Letters*, vol. 15, pp. 578–580, May 2011.
- [5] B. Kohl, "10GBASE-T power budget summary," 2007.
- [6] M. Gupta, S. Grover, and S. Singh, "A feasibility study for power management in LAN switches," in *Network Protocols, 2004. ICNP 2004. Proceedings of the 12th IEEE International Conference on*, pp. 361–371, Oct 2004.
- [7] B. Nordman, "EEE Savings Estimates," *May*, vol. 25, pp. 1–11, 2007.
- [8] IEEE, "IEEE standard for information technology— local and metropolitan area networks— specific requirements— part 3: CSMA/CD access method and physical layer specifications amendment 5: Media access control parameters, physical layers, and management parameters for Energy-Efficient Ethernet," *IEEE Std 802.3az-2010 (Amendment to IEEE Std 802.3-2008)*, pp. 1–302, Oct 2010.
- [9] P. Reviriego, J. A. Hernandez, D. Larrabeiti, and J. A. Maestro, "Burst transmission for Energy-Efficient Ethernet," *IEEE Internet Computing*, vol. 14, pp. 50–57, July 2010.
- [10] K. J. Kim, S. Jin, N. Tian, and B. D. Choi, "Mathematical analysis of burst transmission scheme for IEEE 802.3az energy efficient Ethernet," *Performance Evaluation*, vol. 70, no. 5, pp. 350 – 363, 2013.
- [11] D. Larrabeiti, P. Reviriego, J. Hernandez, J. Maestro, and M. Uruea, "Towards an energy efficient 10 Gb/s optical ethernet: Performance analysis and viability," *Optical Switching and Networking*, vol. 8, no. 3, pp. 131 – 138, 2011. Special Issue on Green Communications and Networking.
- [12] M. A. Marsan, A. F. Anta, V. Mancuso, B. Rengarajan, P. R. Vasallo, and G. Rizzo, "A simple analytical model for Energy Efficient Ethernet," *IEEE Communications Letters*, vol. 15, pp. 773–775, July 2011.
- [13] R. Bolla, R. Bruschi, A. Carrega, F. Davoli, and P. Lago, "A closed-form model for the IEEE 802.3az network and power performance," *IEEE Journal on Selected Areas in Communications*, vol. 32, pp. 16–27, January 2014.
- [14] P. Reviriego, J. A. Hernandez, D. Larrabeiti, and J. A. Maestro, "Performance evaluation of Energy Efficient Ethernet," *IEEE Communications Letters*, vol. 13, pp. 697–699, Sept 2009.
- [15] M. Mostowfi and K. Christensen, "An energy-delay model for a packet coalescer," in *Southeastcon, 2012 Proceedings of IEEE*, pp. 1–6, March 2012.
- [16] N. Akar, "Delay analysis of timer-based frame coalescing in Energy Efficient Ethernet," *IEEE Communications Letters*, vol. 17, pp. 1459–1462, July 2013.

- [17] S. Herrera-Alonso, M. Rodriguez-Perez, M. Fernandez-Veiga, and C. Lopez-Garcia, "How efficient is energy-efficient ethernet?," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2011 3rd International Congress on*, pp. 1–7, Oct 2011.
- [18] S. Herrera-Alonso, M. Rodriguez-Perez, M. Fernandez-Veiga, and C. Lopez-Garcia, "A power saving model for burst transmission in Energy-Efficient Ethernet," *IEEE Communications Letters*, vol. 15, pp. 584–586, May 2011.
- [19] S. Herrera-Alonso, M. Rodriguez-Perez, M. Fernandez-Veiga, and C. Lopez-Garcia, "Optimal configuration of Energy-Efficient Ethernet," *Computer Networks*, vol. 56, no. 10, pp. 2456 – 2467, 2012. Green communication networks.
- [20] S. Herrera-Alonso, M. Rodriguez-Perez, M. Fernandez-Veiga, and C. Lopez-Garcia, "A GI/G/1 model for 10 Gb/s Energy Efficient Ethernet links," *IEEE Transactions on Communications*, vol. 60, pp. 3386–3395, November 2012.
- [21] D. P. Bertsekas, R. G. Gallager, and P. Humblet, *Data networks*, vol. 2. Prentice-Hall International New Jersey, 1992.
- [22] M. Yadin and P. Naor, "Queueing systems with a removable service station," *OR*, pp. 393–405, 1963.
- [23] D. P. Heyman, "The T-policy for the M/G/1 queue," *Management Science*, vol. 23, no. 7, pp. 775–778, 1977.
- [24] L. Kleinrock, *Theory, volume 1, Queueing systems*. Wiley-interscience, 1975.